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Constraining aerosol indirect forcing from satellite data

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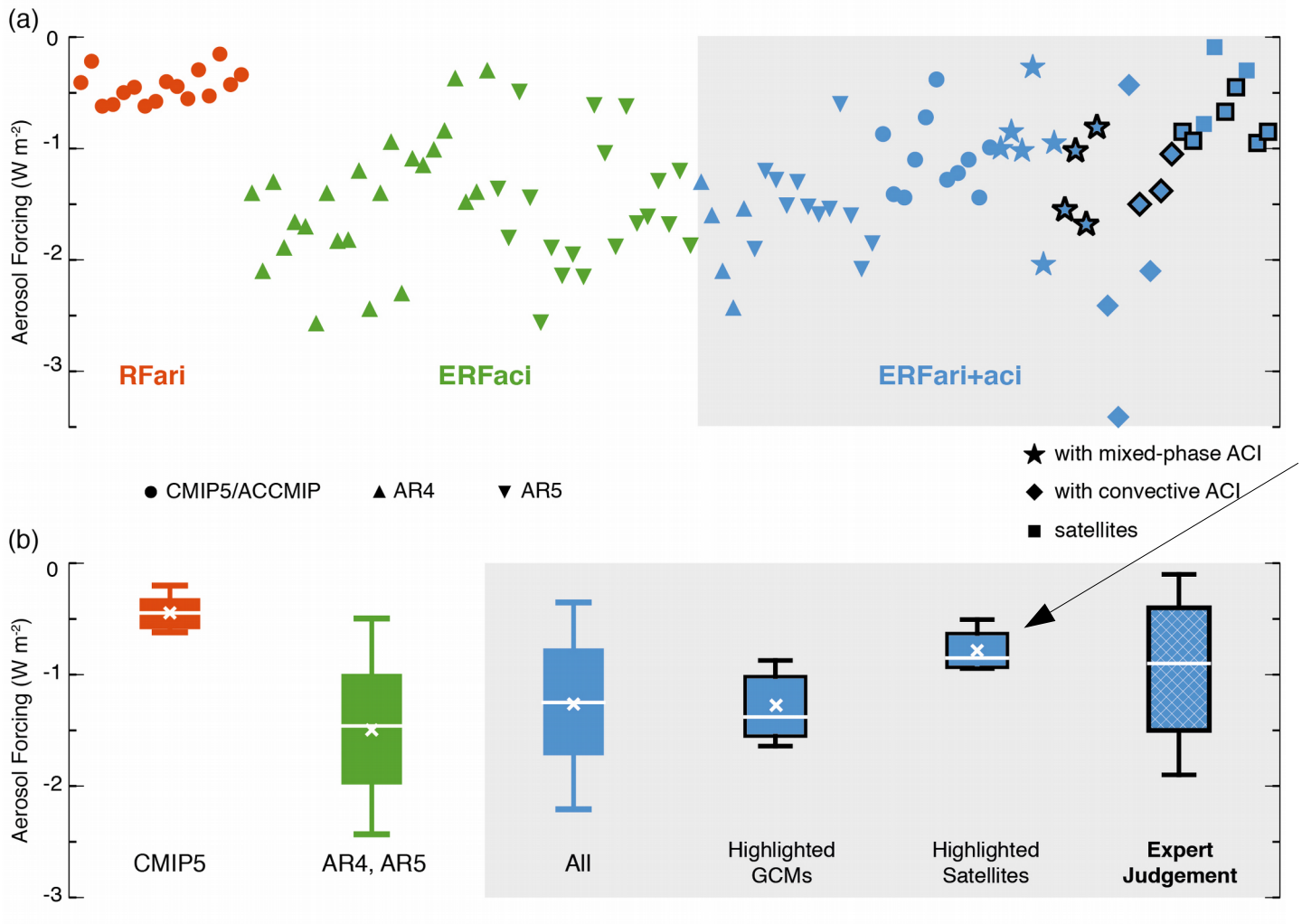
Aerosol Radiative Forcing



Estimates based on satellite data are often smaller than model-based ones

They are weighted higher than models - A good constraint is important!

Boucher et al., 2013

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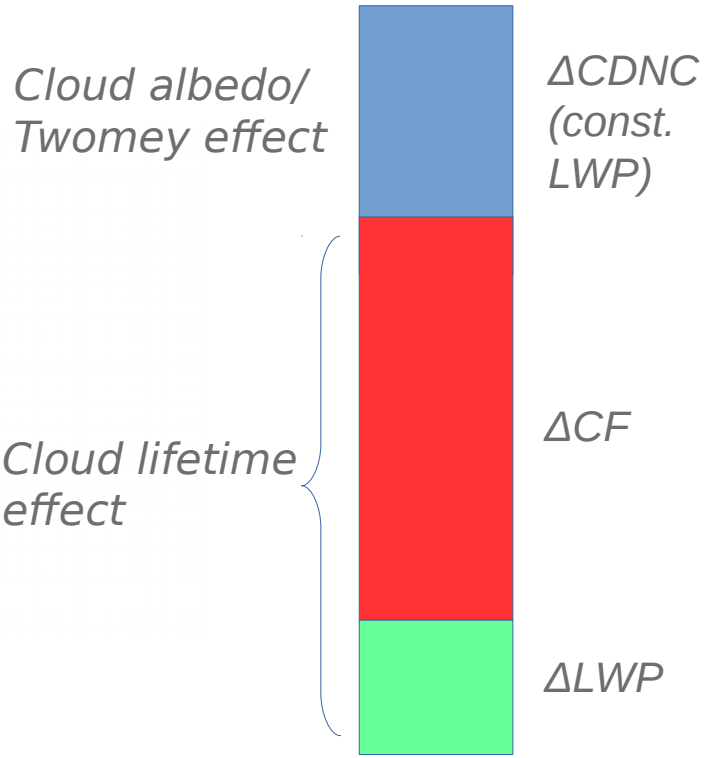
Towards a complete estimate

Many studies have investigated the Twomey effect (a change in albedo with changing droplet number)

There are some constraints on changes in other cloud properties (CF, LWP)

This work demonstrates a method for combining these into a single forcing estimate (for liquid clouds)



AOD – aerosol optical depth
CF – cloud fraction
CDNC – Cloud droplet number concentration
LWP – liquid water path

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Causality

We want to know the change in albedo, given a change is made in the aerosol optical depth (AOD)

$$\Delta\alpha = \sum_{AOD} P(\alpha | do(AOD)) \left(P(AOD) - P(AOD)_{nat} \right)$$

This is not necessarily the same as the observed relationship

$$P(\alpha | do(AOD)) \neq P(\alpha | AOD)$$

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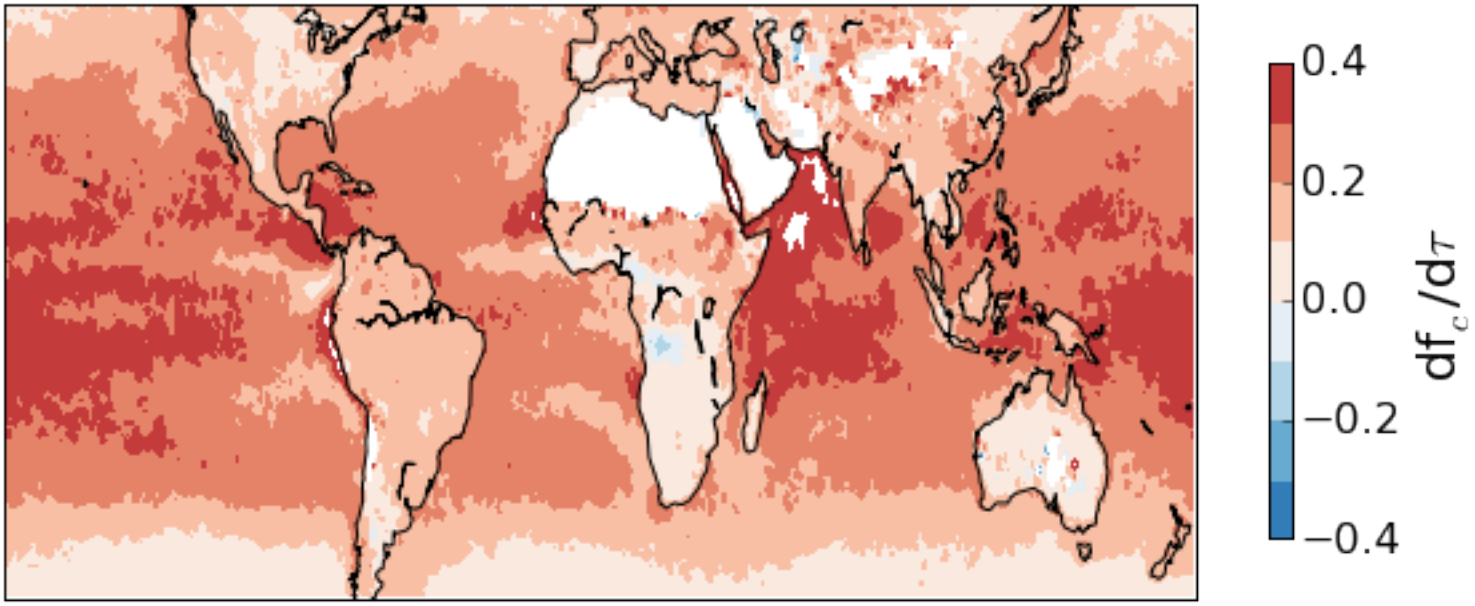
Causality

Albedo strongly related to cloud fraction (CF)



Data from MODIS Aqua (used throughout this work)

The CF – AOD relationship is strongly influenced by humidity

Grandey et al., 2013

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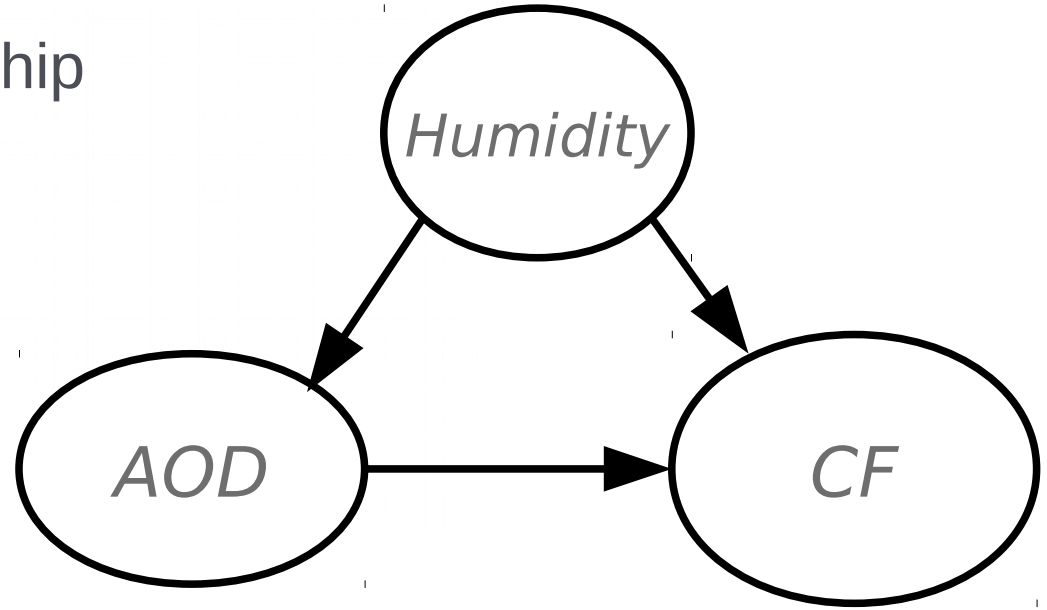
Causality

Meteorology (particulrly relative humidity) obscures the causal aerosol relationship



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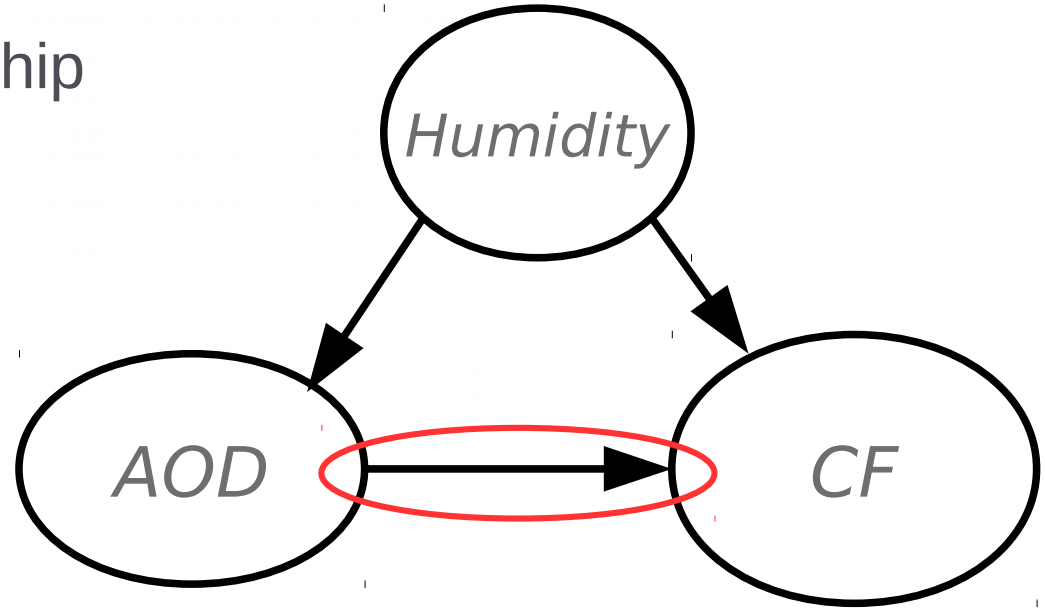

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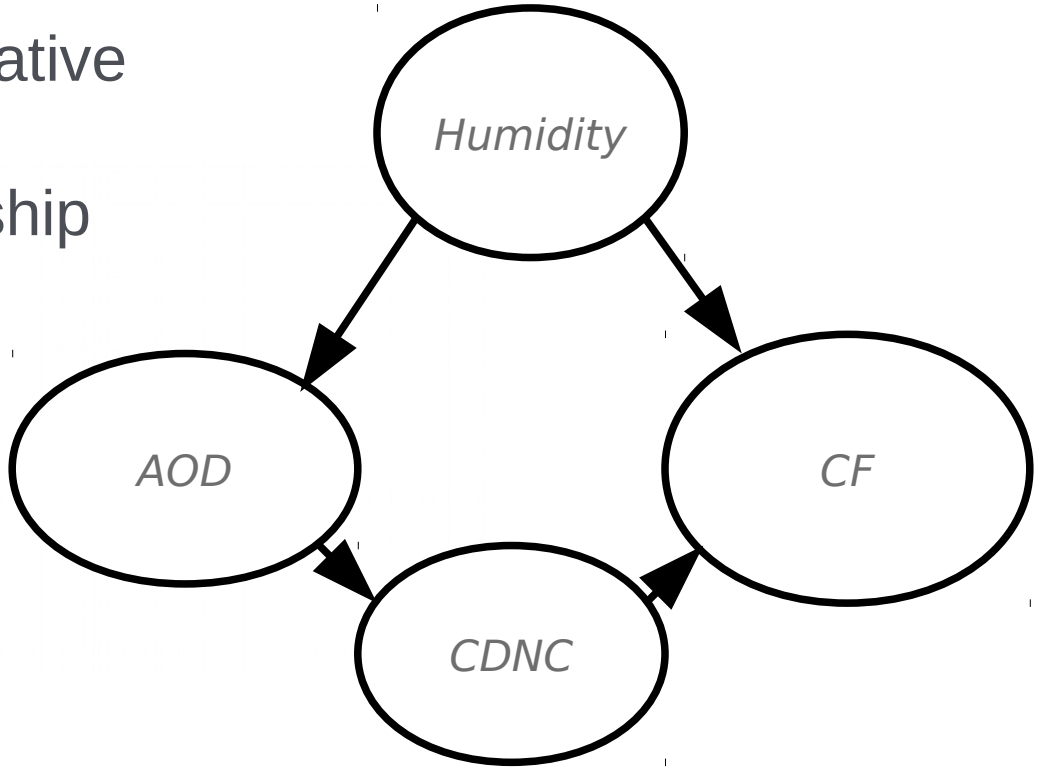
Causality

Meteorology (particulrly relative humidity) obscures the causal aerosol relationship

One solution is to include mediating variables

Separates the causal relationship from confounding factors



AOD – aerosol optical depth
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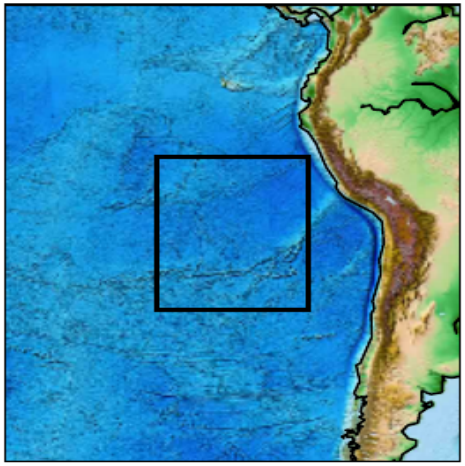
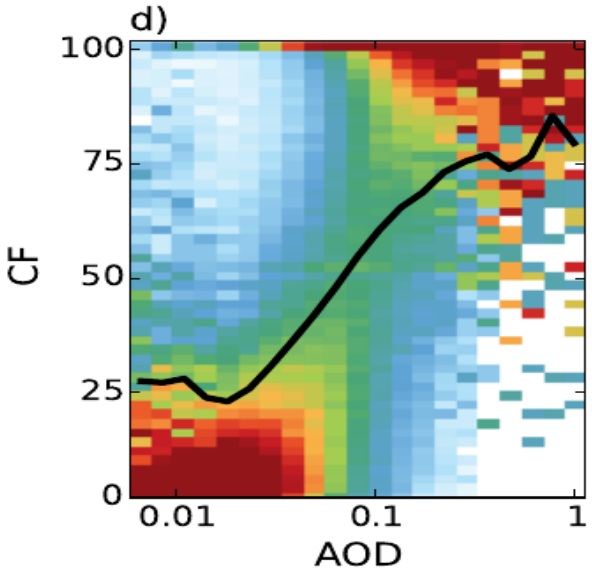
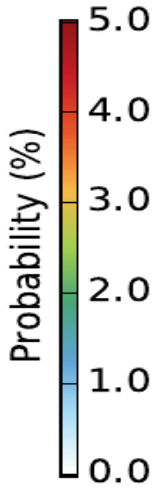
AOD-CDNC-CF example







Gryspeerdt et al., 2016

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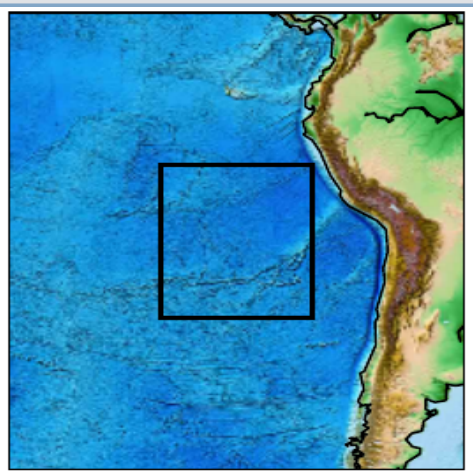
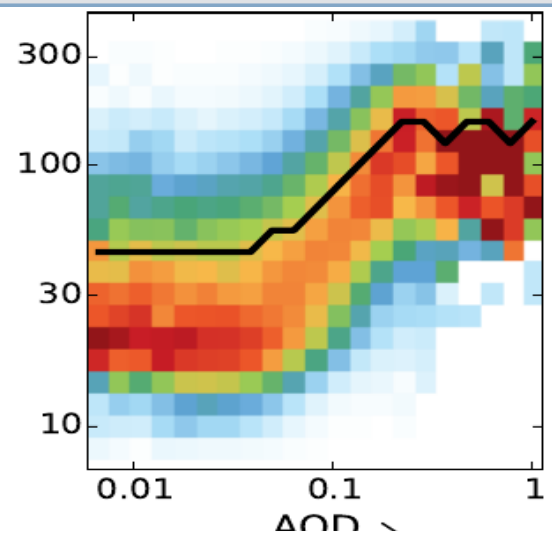
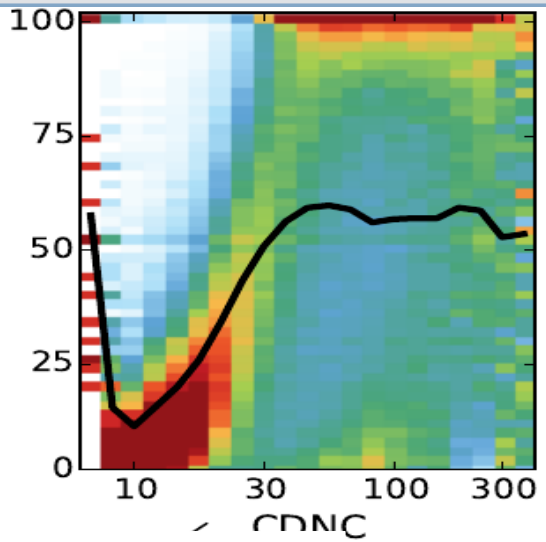
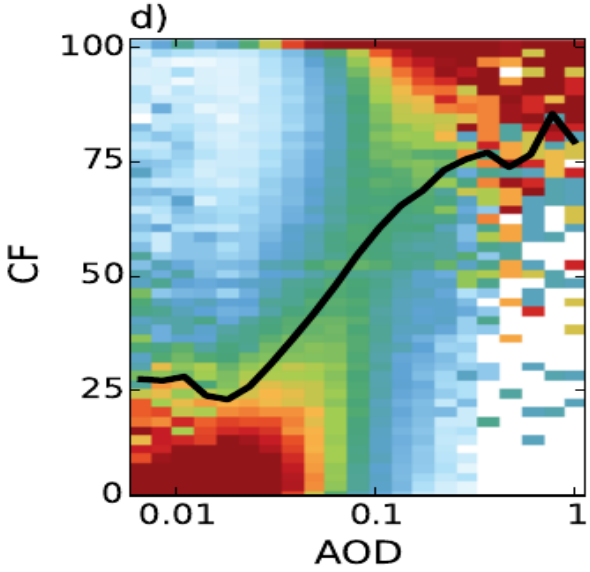
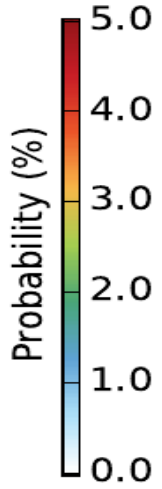
AOD-CDNC-CF example











Gryspeerdt et al., 2016

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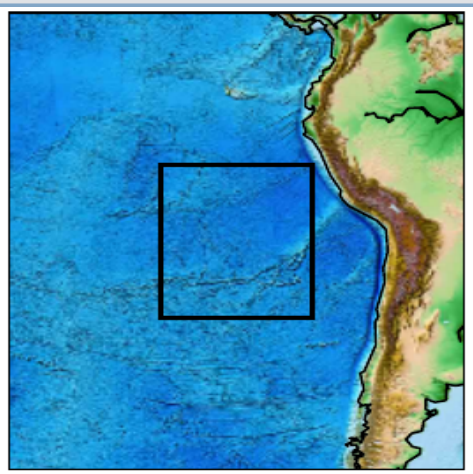
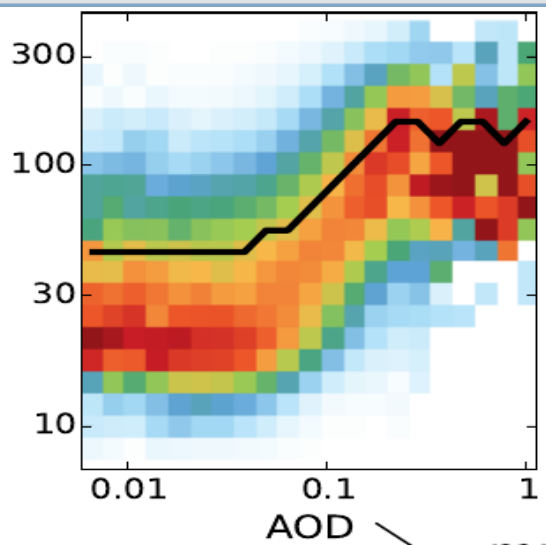
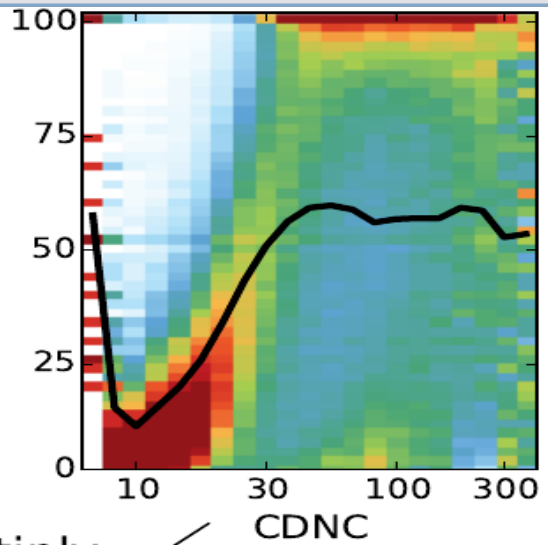
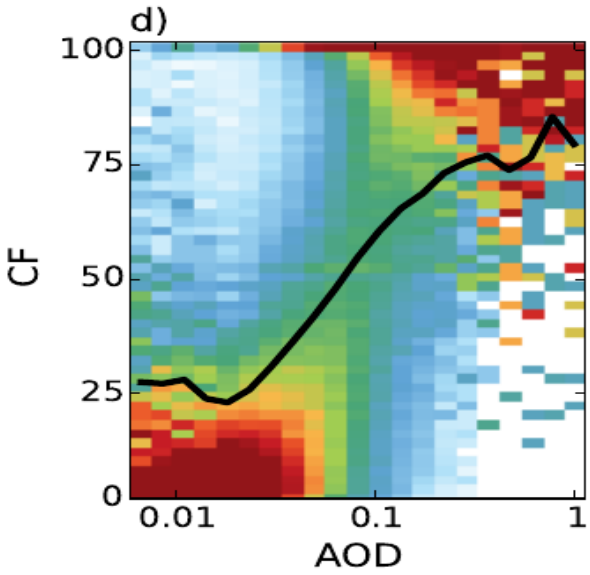
AOD-CDNC-CF example

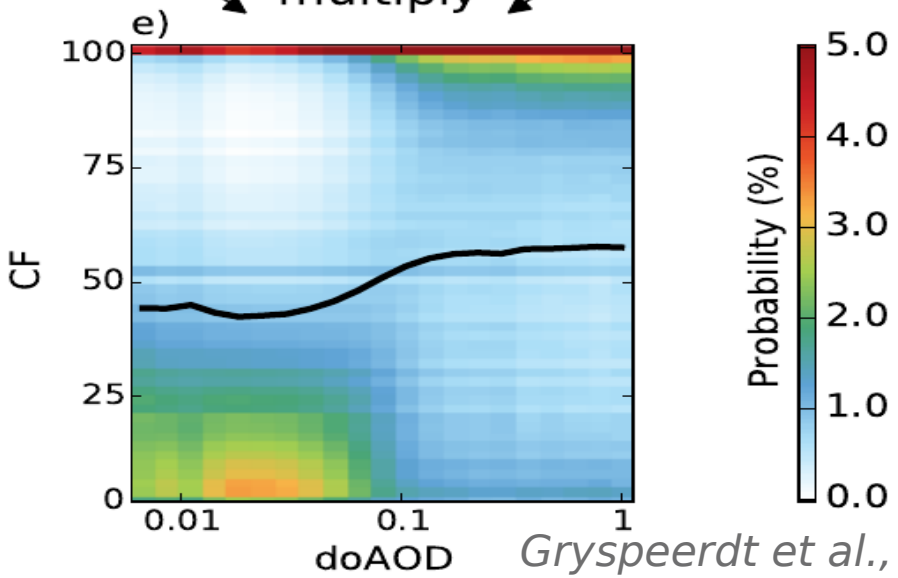






multiply





Gryspeerdt et al., 2016

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Building the forcing estimate

Using CDNC as a mediating variable, we can decompose the relationship into cloud and aerosol components

$$Forcing = \sum P(\alpha | CF, CDNC, LWP) \times P(CF, LWP | CDNC) \times P(CDNC | AOD) \times \Delta AOD$$

AOD – aerosol optical depth
CF – cloud fraction
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Radiation

Single global histogram

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Radiation

Single global histogram

Cloud

Varies with cloud type, meteorolgy

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Radiation

Single global histogram

Cloud

Varies with cloud type, meteorolgy

Aerosol

Varies with aerosol type

AOD – aerosol optical depth
CF – cloud fraction
CDNC – Cloud droplet number concentration
LWP – liquid water path

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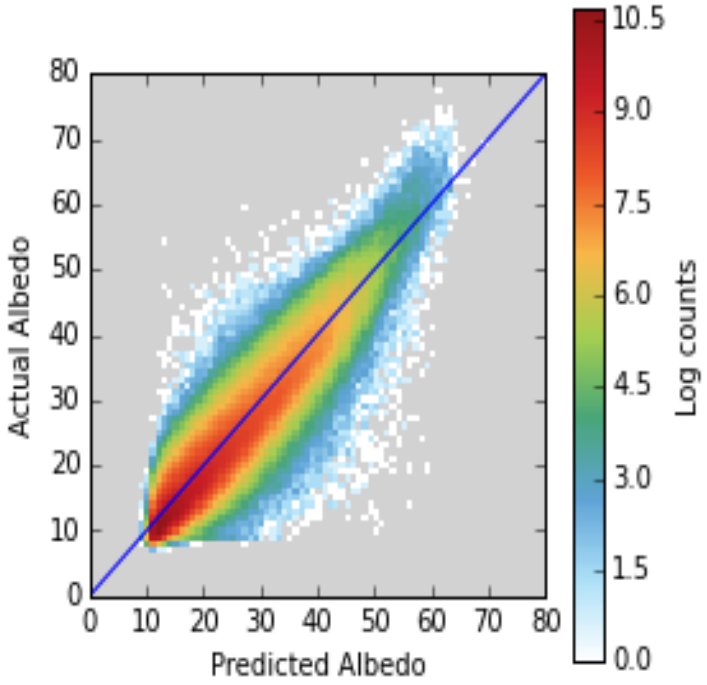
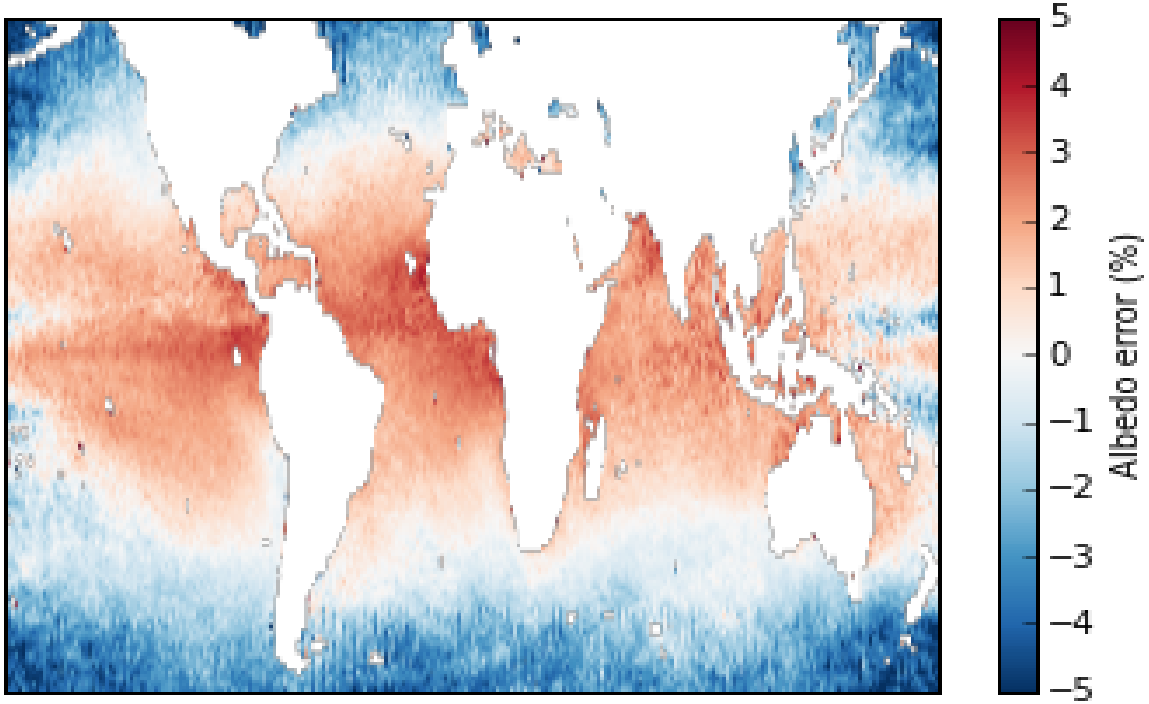
Calculating the albedo

Comparison between CERES albedo and that predicted from the joint histogram of cloud properties (CF, CDNC, LWP)





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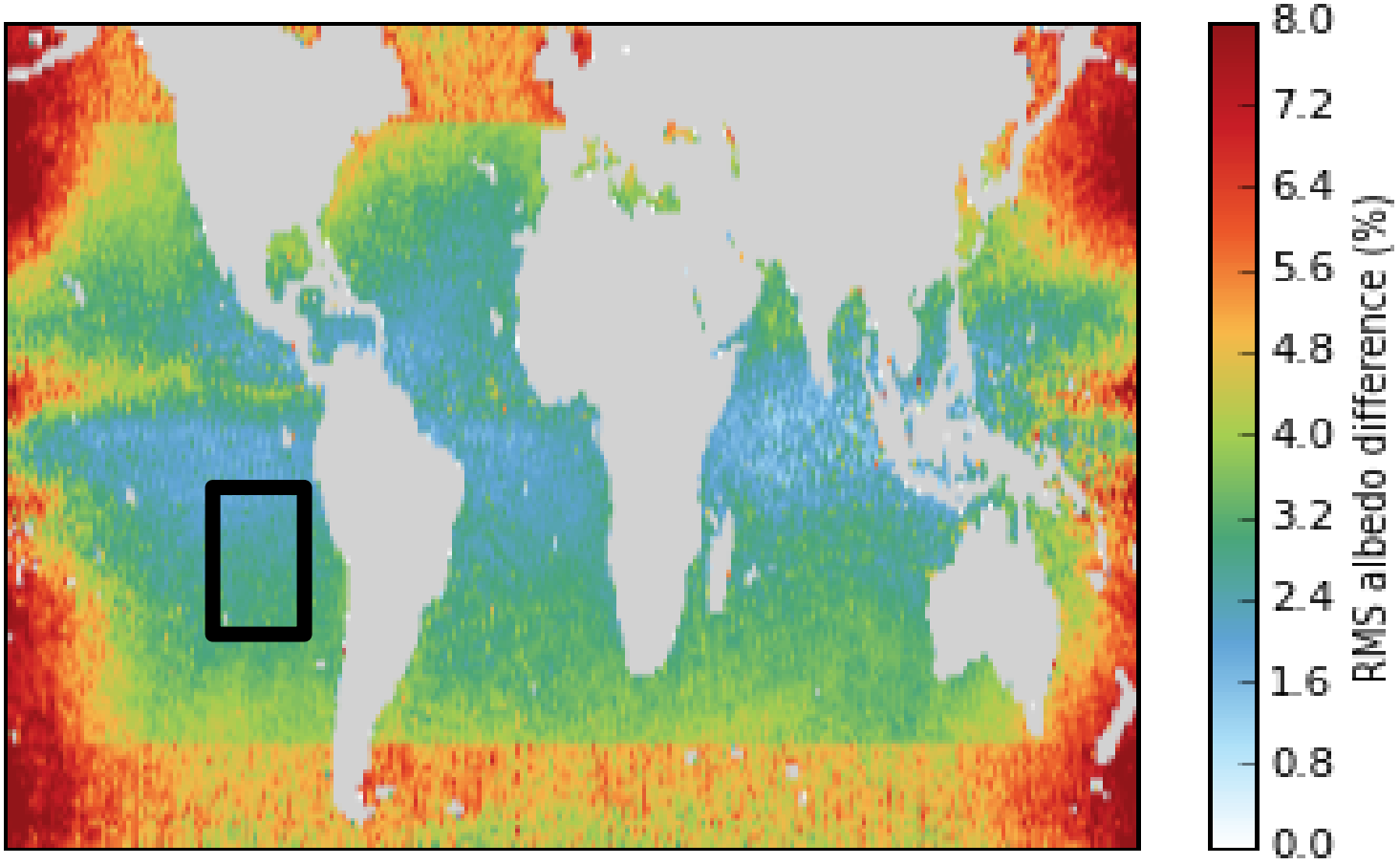
Calculating the albedo

Random errors higher where CERES and MODIS days don't line up



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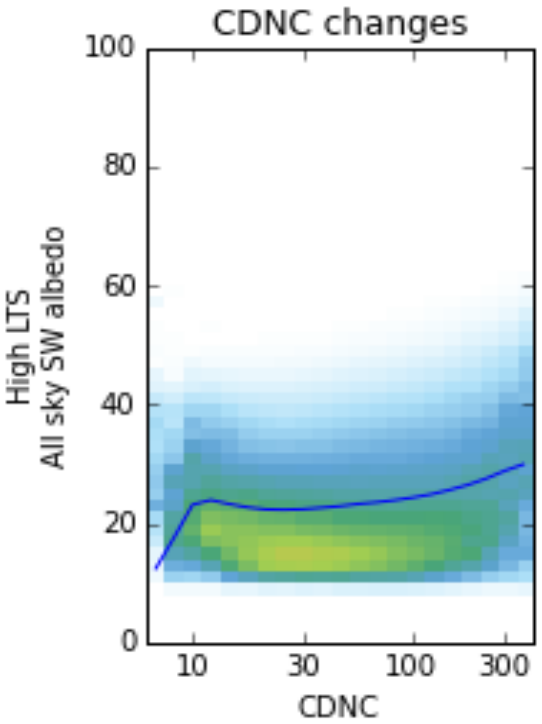
Albedo changes



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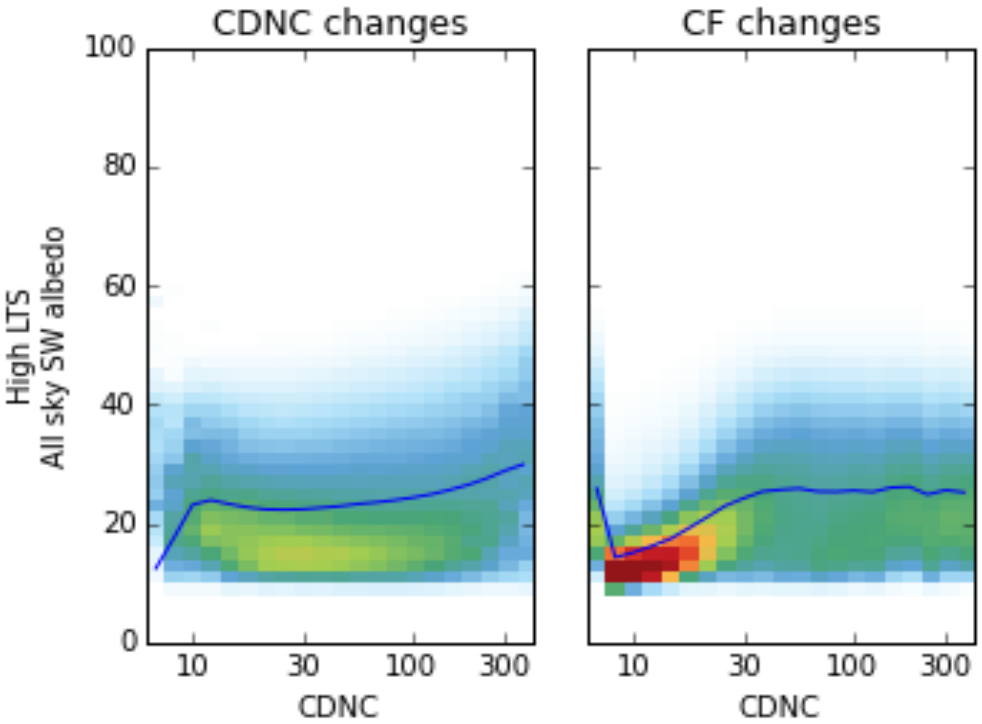
Albedo changes



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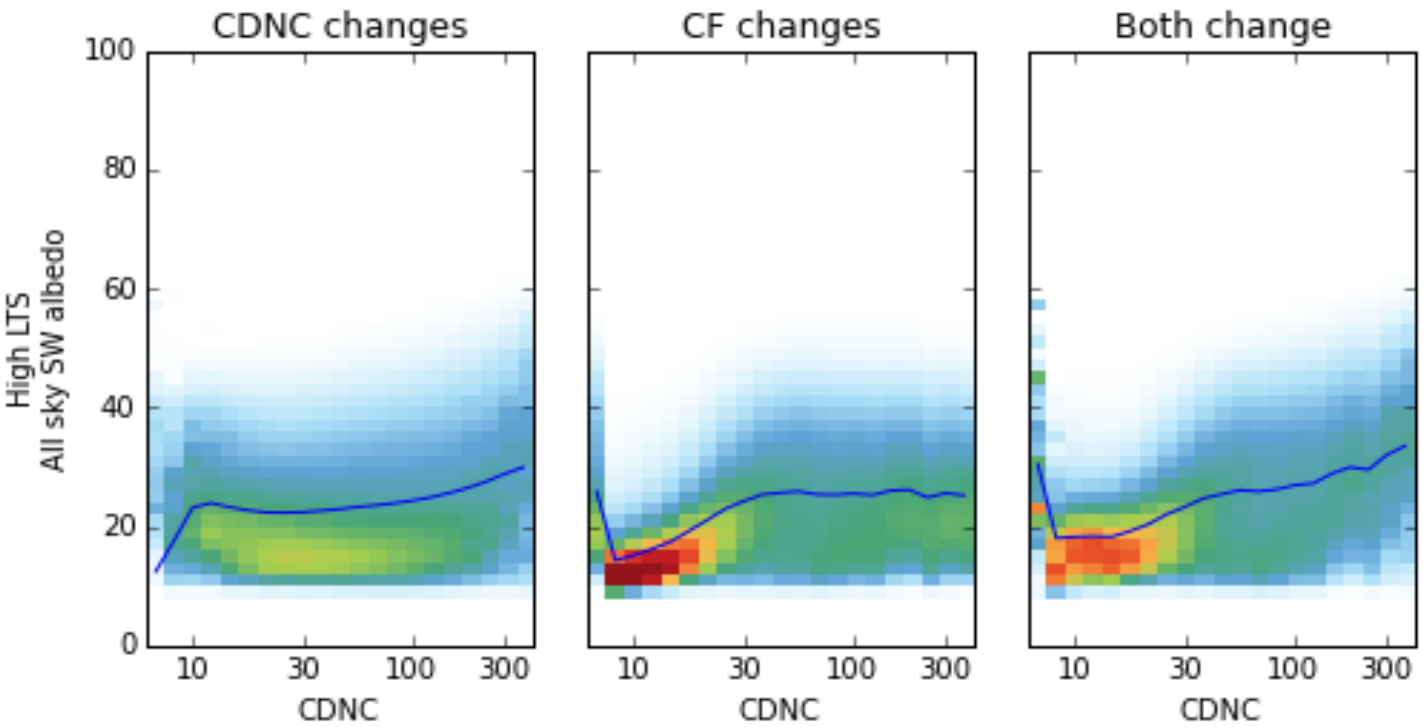
Albedo changes



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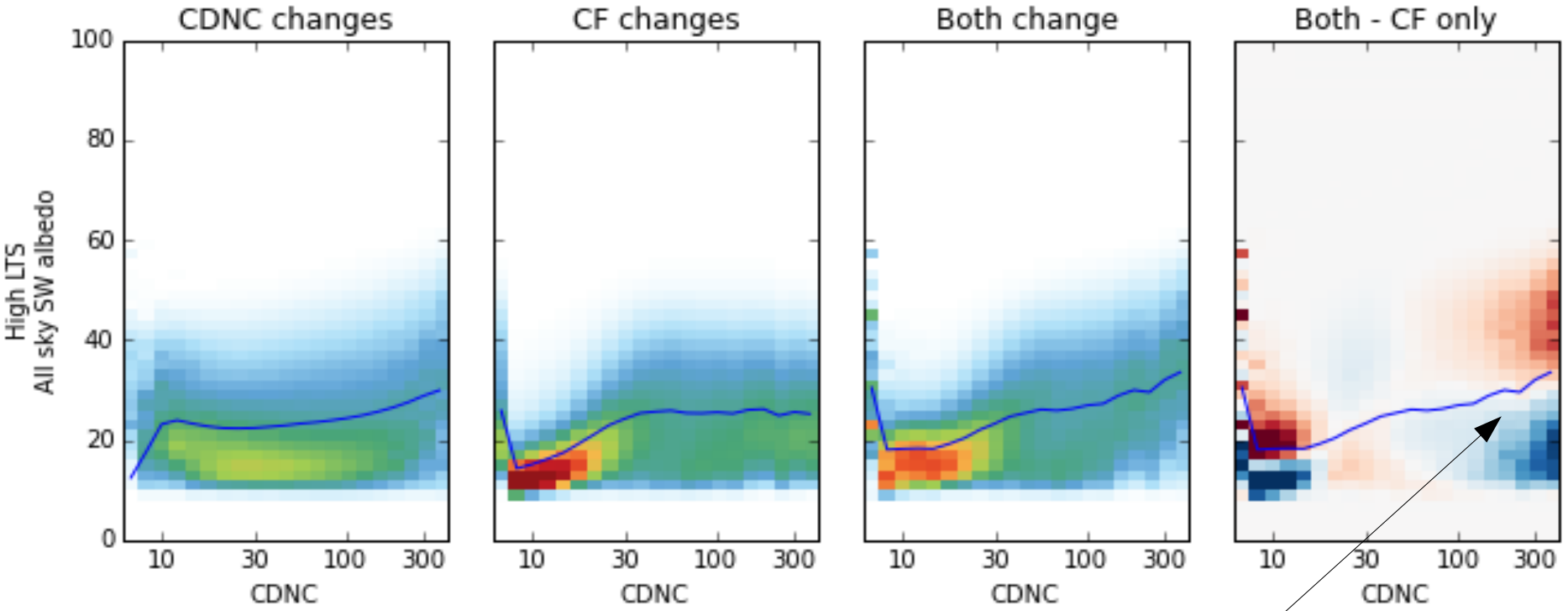
Albedo changes



Cloud albedo effect becomes important at higher CDNC

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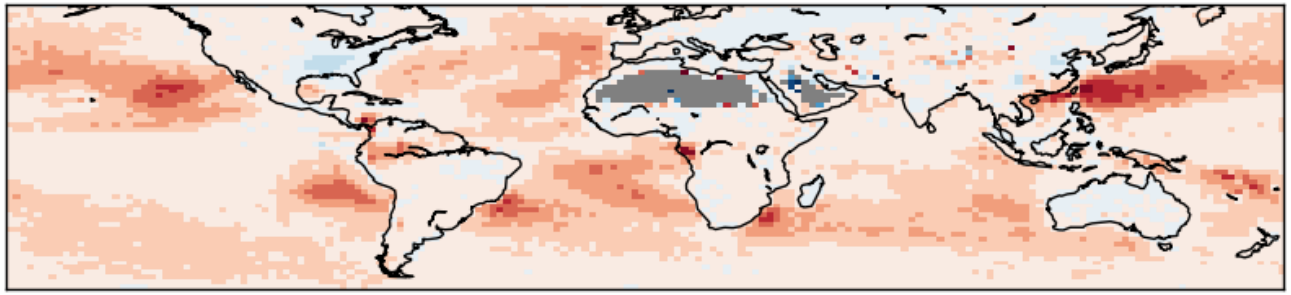
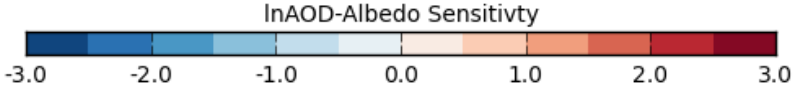
Global sensitivity



Cloud fraction effect (constant CDNC)



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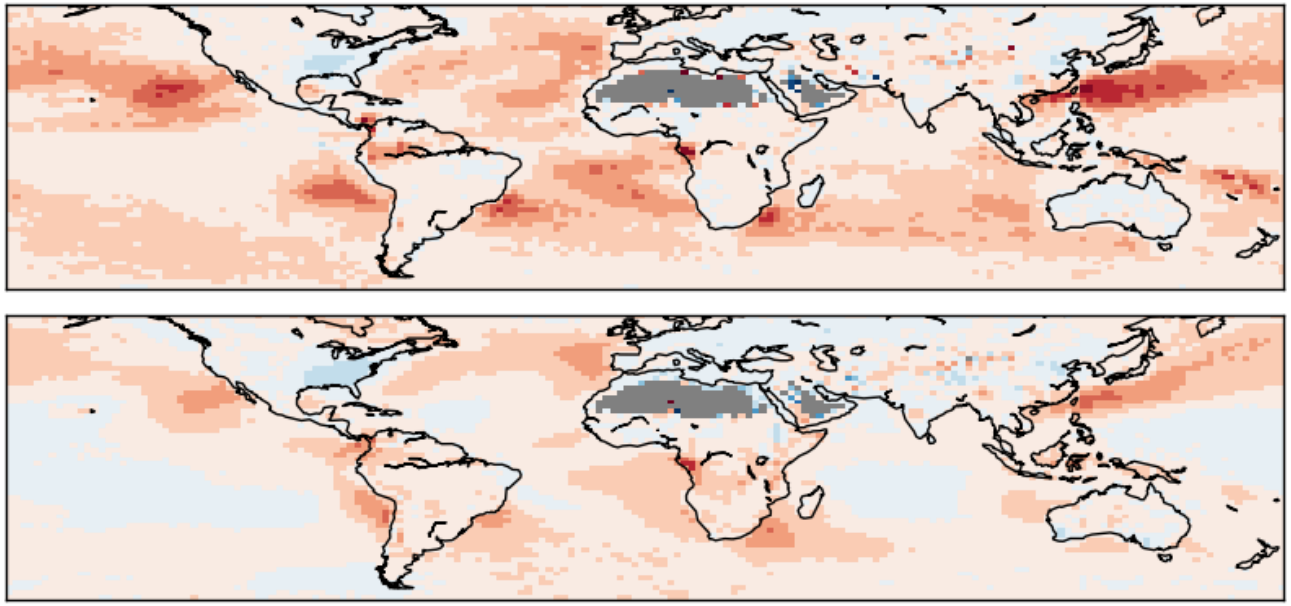
Global sensitivity



Cloud fraction effect (constant CDNC)

Cloud albedo effect (constant CF)

lnAOD-Albedo Sensitivty

-3.0 -2.0 -1.0 0.0 1.0 2.0 3.0

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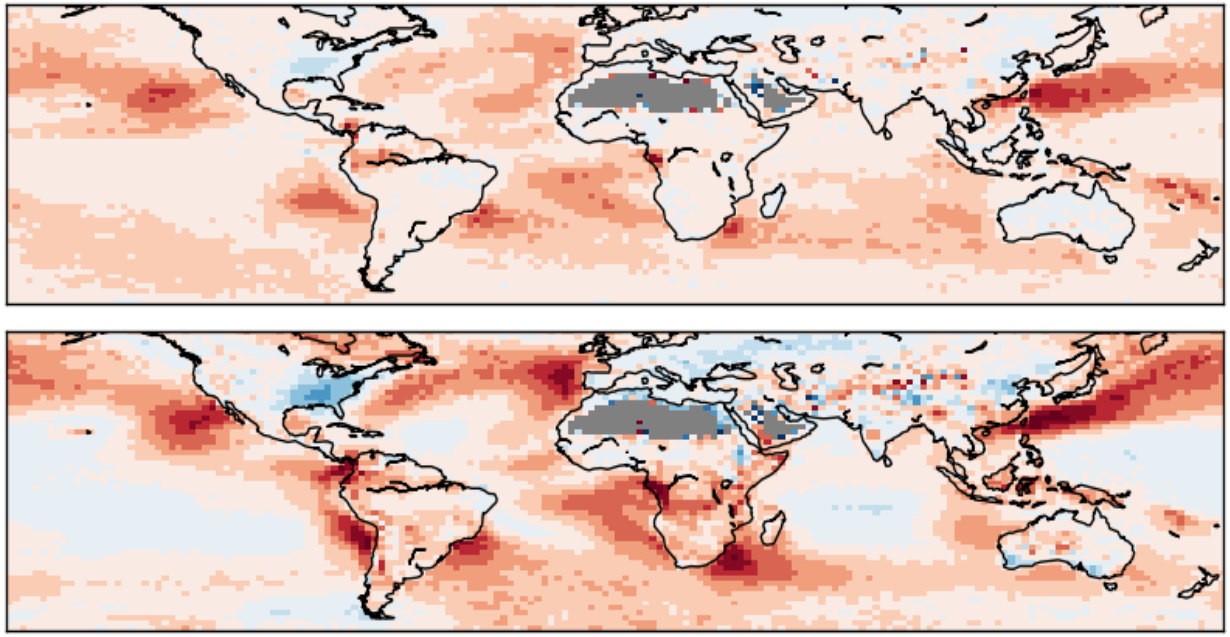
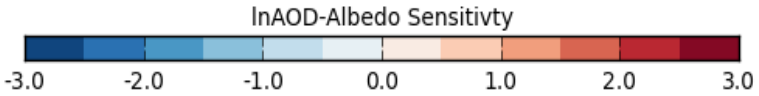
Global sensitivity



Cloud fraction effect (constant CDNC)

*2 * Cloud albedo effect (constant CF)*



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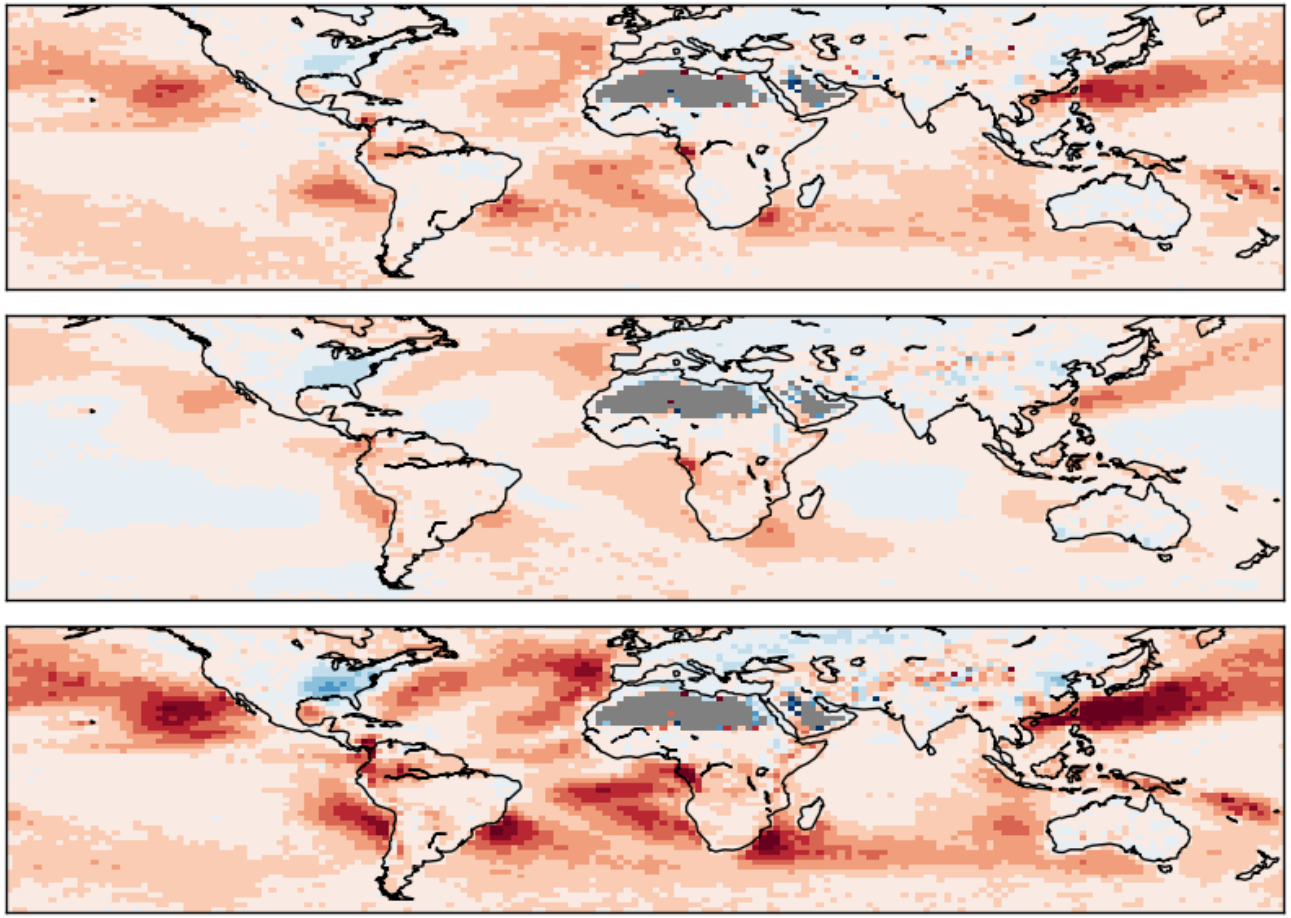
Global sensitivity



Cloud fraction effect (constant CDNC)

Cloud albedo effect (constant CF)

Combined sensitivity

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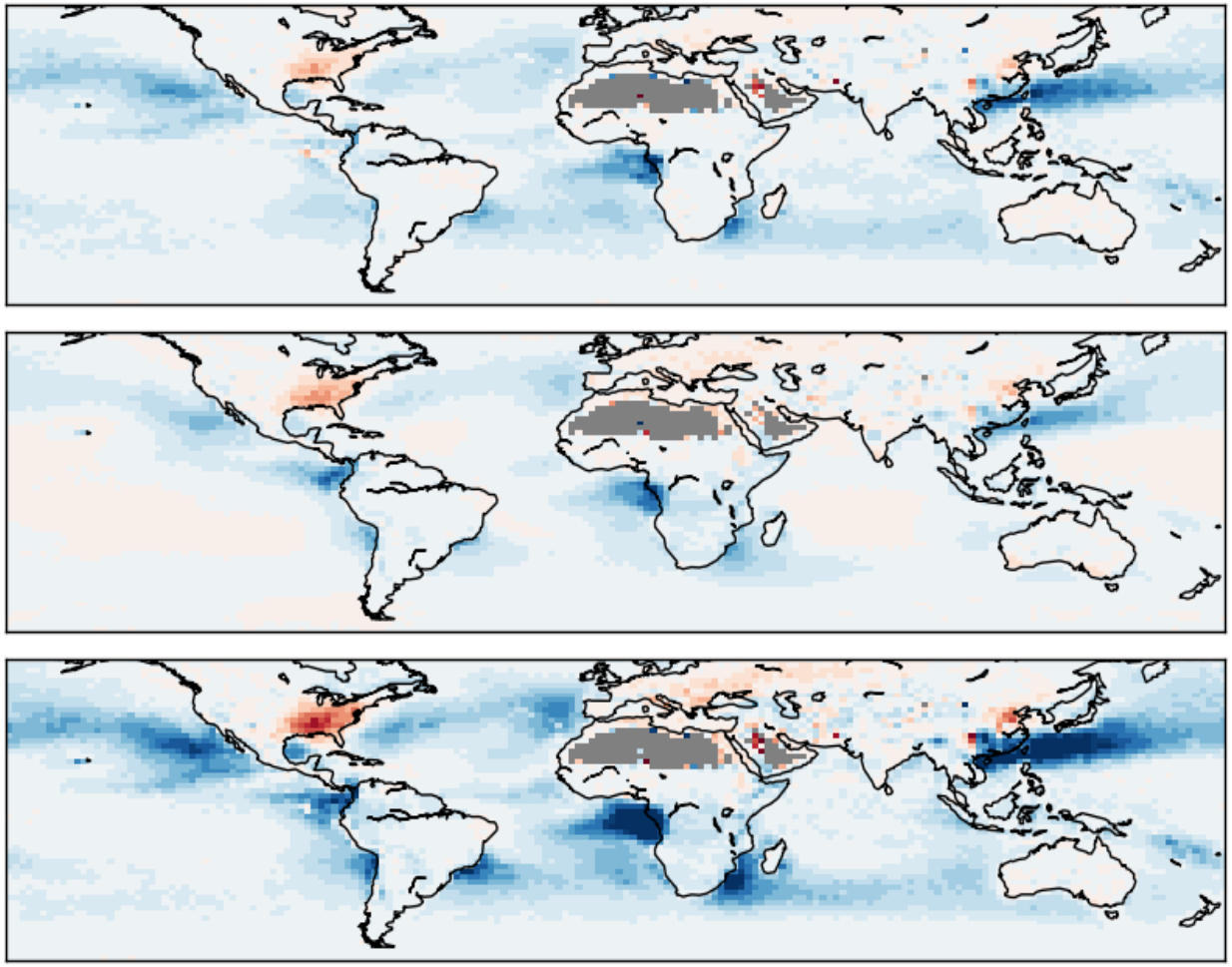
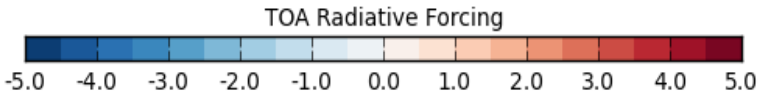
Implied forcing



Cloud fraction effect (constant CDNC)
-0.49 Wm^{-2}

Cloud albedo effect (constant CF)
-0.29 Wm^{-2}

Combined
-0.75 Wm^{-2}



Using MACC anthropogenic aerosol fraction (Bellouin et al., 2013)

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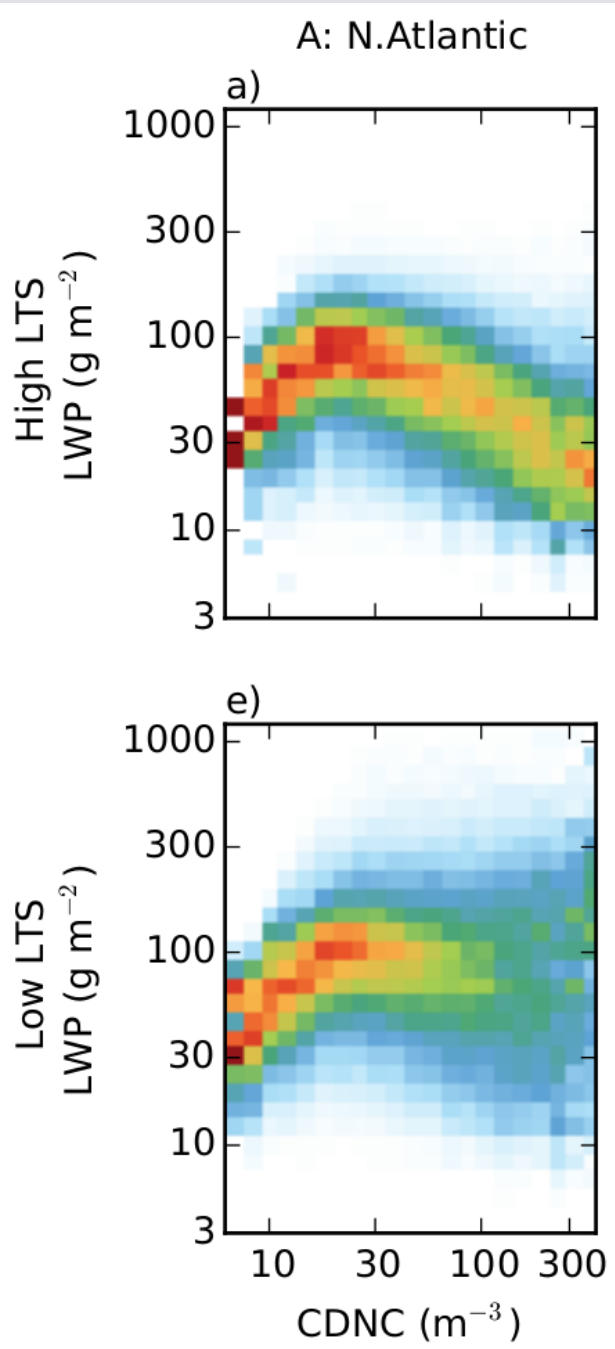
What about the LWP?

Relationship to CDNC is tricky to understand

- *Relationship to AOD is not better (related to CF...)*

Some studies suggest increase in LWP with increasing aerosol

- *CDNC-LWP relationship often shows decrease*



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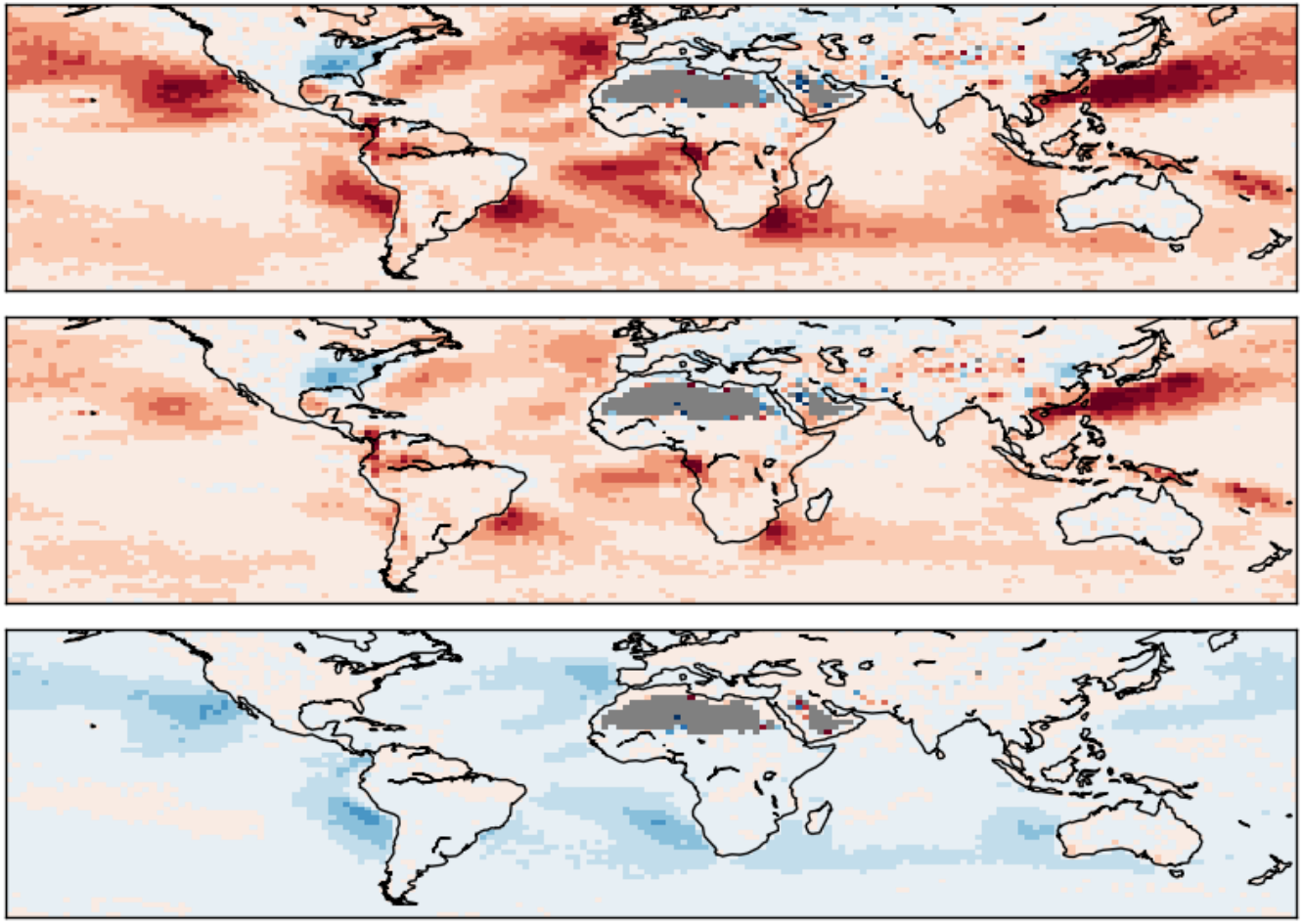
What about the LWP?



Cloud fraction and Twomey

Including LWP

Difference (due to LWP changes)

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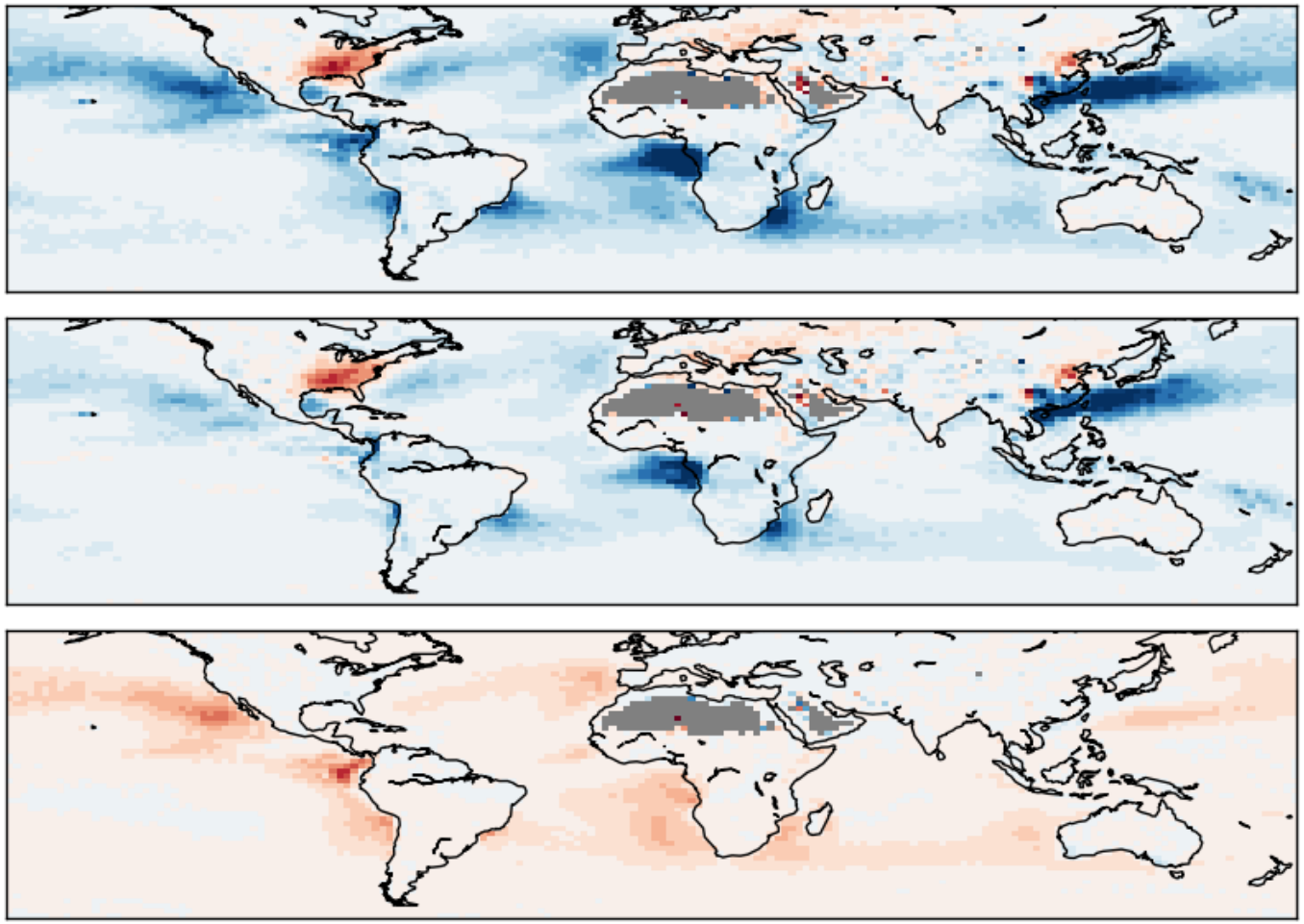
What about the LWP?



Cloud fraction and Twomey
-0.75 Wm^{-2}

Including LWP
-0.50 Wm^{-2}

Difference (due to LWP changes)
+0.25 Wm^{-2}

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Conclusions

Mediating variables mitigate the impact of local meteorology

- *Can get closer to causal relationships*

Joint histogrm P(albedo | CF, CDNC, LWP) allows a combined forcing calculation

- *Maintain non-linearities*

Allows for expansion to other aerosol effects

- *Determining the LWP change still problematic*

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Linking aerosol to all-sky albedo

$$\sum_{LWP} P(\alpha|CF, CDNC, LWP)\, P(LWP|CDNC) = P(\alpha|CF, CDNC)$$

Remove conditional probabilities?

$$P(LWP|CDNC) = P(LWP)$$

Add the CF dependence on CDNC

$$\sum_{CF} P(\alpha|CF, CDNC)\, P(CF|CDNC) = P(\alpha|CDNC)$$

Add in aerosol activation step

$$\sum_{CDNC} P(\alpha|CDNC)\, P(CDNC|AOD) = P(\alpha|do(AOD))$$

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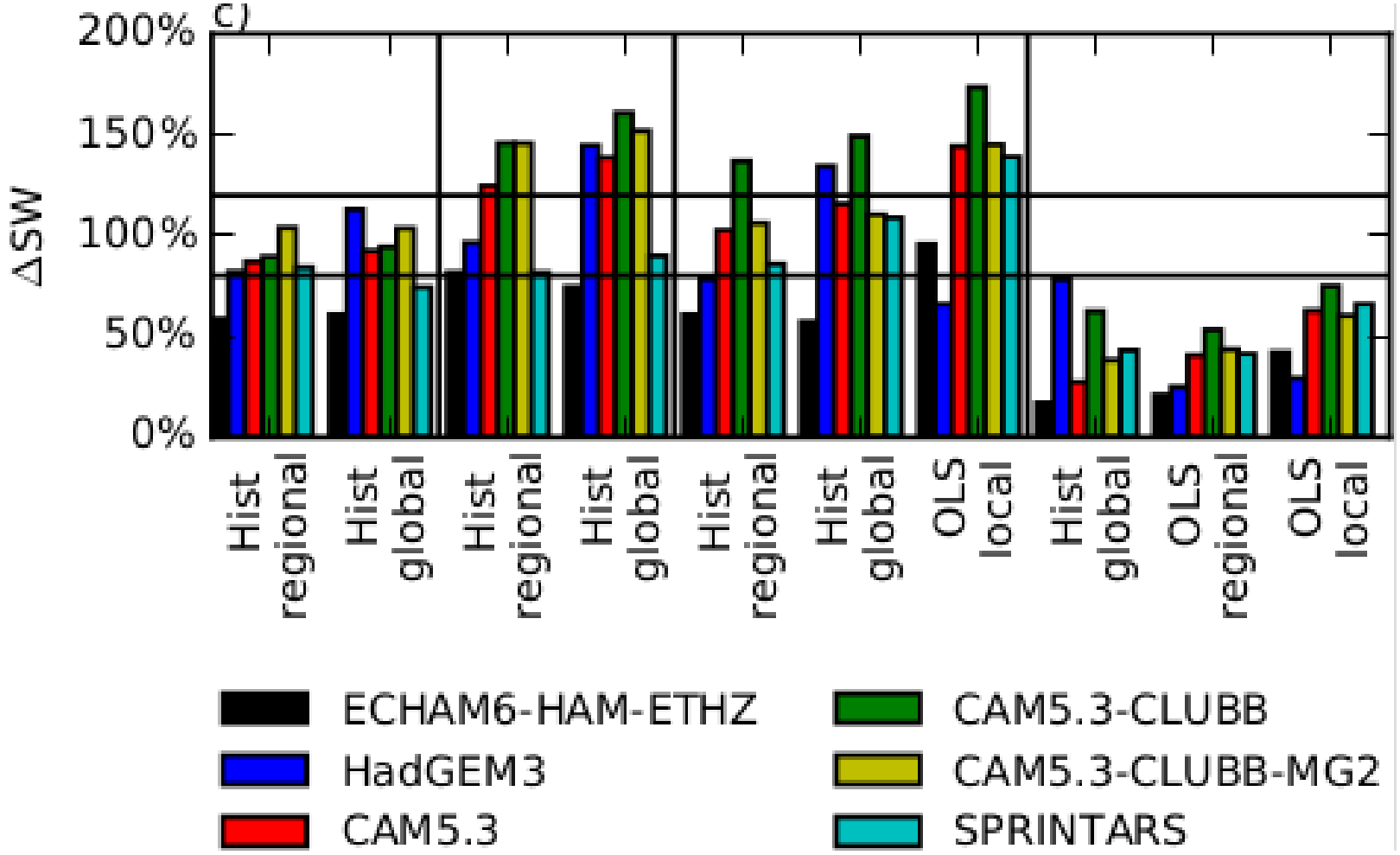
Why not radiative transfer?

Radiative transfer?
Requires the 'retrieved' CDNC → 'real' CDNC relationship is known
Often not entirely clear as relies on cloud adiabaticity

- *Histogram only requires monotonic relationship between 'real' and 'retrieved' CDNC*


c)
200%
150%
100%
50%
0%
ΔSW
Hist regional
Hist global
Hist regional
Hist global
Hist regional
Hist global
OLS local
Hist global
OLS regional
OLS local
ECHAM6-HAM-ETHZ
HadGEM3
CAM5.3
CAM5.3-CLUBB
CAM5.3-CLUBB-MG2
SPRINTARS

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